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Academic centers and/as industrial consortia in American microelectronics research

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ABSTRACT
In the U.S., in the late 1970s and early 1980s, academic research centers that were tightly linked to the semiconductor industry began to proliferate – at exactly the same time as the first academic start-up companies in biotech, and slightly before the first U.S. industrial semiconductor research consortia. I show that some of the same factors stimulated institutional entrepreneurs to found both industrial consortia and academic centers. But industrial consortia and academic centers were not just co-emergent. They were also commingled organizational forms – consortia took advantage of ties to academic centers and *vice versa*. Thus, any understanding of the one must account for the other as well. However, academic microelectronics research centers possessed greater flexibility to forge alliances with other industries than did industrial consortia – a flexibility they increasingly took advantage of in the 1990s, as their importance to their original patrons in the semiconductor industry receded.

KEYWORDS
Semiconductors; biotechnology; Stanford; Cornell; VLSI

Introduction: co-emergent institutional innovation in microelectronics research

The editors of this special issue on academic entrepreneurship and institutional change have defined entrepreneurship as 'the process by which actors identify opportunities for the future, allocate resources to them, and legitimize their actions'. Academic institutional entrepreneurship, then, is the process by which actors identify opportunities for universities and allied organizations to forge new institutions, i.e. novel procedures, norms, rules, cognitive frames, and bureaucratic lines-of-sight. Of course, this type of academic entrepreneurship does not take place in a vacuum, but rather in an environment that includes a variety of non-academic actors and organizations. Academic institutional entrepreneurs identify opportunities in large part by observing events in domains to which universities are connected (or would like to be connected) such as industry and government.

At the same time, institutional entrepreneurs outside the university are capable of making the same observations and therefore of identifying the same opportunities. Any analysis of academic entrepreneurship, therefore, must account for actors outside the university who:

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(A) form their own innovative institutions that mirror or compete with institutional innovations that simultaneously develop within universities; and/or (B) stimulate and aid academic actors to forge new institutions that will benefit both the university and its extra-academic partners; and/or (C) develop their own innovative institutions that link up with (or sometimes fail to link up with) those emerging in academia.

In this article, I explore all three of these processes (A, B, and C) in fields related to microelectronics and semiconductor research from the late 1970s to the mid-1990s. This period was marked by the novel and frequent founding of university centers focusing on semiconductor research. But this was also the time when another new organizational form emerged with a very similar mission and for some of the same reasons: the industrial microelectronics research consortium – an example of (A). Actors in industry and especially in government stimulated or aided the formation of both university centers and industrial consortia in microelectronics – an example of (B). Because of these similarities in the environments that incubated them, and similarities in the specific guidance provided by their stakeholders, university centers and industrial consortia were convergent institutions – they mirrored each other in many ways. My stronger claim, however, is that they were also commingled institutions: consortia took advantage of resources offered by academic centers, and *vice versa*.

In the short term, many of the institutional innovations inspired by the U.S. semiconductor industry's late 1970s woes were found wanting: some of the earliest academic research centers and industrial consortia disappeared relatively quickly. Over the longer term, consortia became a permanent feature of the landscape in part by claiming a special expertise in managing large, multi-university networks of academic researchers (Khan, Hounshell, Fuchs 2015). Academic microelectronics research centers (MRCs), meanwhile, secured their legitimacy in part through a difficult process of adjusting their practices to conform with the expectations of stakeholders in industry and government. That was not enough, however. The importance of the semiconductor industry to academic semiconductor research centers has decreased steadily since the early 1990s. The final piece of my argument, therefore, is that these centers have had to find new patrons and make new kinds of connections afforded by their position within the university. Academic entrepreneurs look to an external environment that simultaneously looks to them – and since that environment continuously changes the entrepreneur must continuously innovate to catch up or stay ahead.

(Changing) environmental factors

Understanding institutional innovation in semiconductor research is important in its own right. The microelectronics industry, after all, contributes more to U.S. GDP than any other manufacturing industry and takes similar pride of place in the economies of many other nations. However, the semiconductor case is doubly useful because it illuminates aspects of co-emergent academic and industrial institutional entrepreneurship (aided from both ends by the state) that have been obscured in the dominant literature on post-1970 academic entrepreneurs in biotechnology. Academic centers rarely appear in influential studies of early biotech pioneers such as Cetus, Genentech, Hybritech (Smith 2011; Rasmussen 2014; Kenney 1988; McKelvey 1996; Casper 2014). Similarly, consortia appear not to have been as important in biotech as in semiconductors; while research partnerships are common in biotech, they tend to involve two or perhaps three firms rather than a dozen or more. Biotech partnerships are also usually focused on some specific end-goal, and therefore tend to run their course and then dissolve, often unhappily and accompanied by lawsuits (de Rond 2003). In the semiconductor industry, however, research consortia that are large, enduring, and retain an ever-changing portfolio of projects with a variety of endpoints have been the norm since at least the early 1980s (Grindley, Mowery, and Silverman 1994).

My own view is that examples of co-emergent, convergent institutional entrepreneurship by academic and non-academic actors could probably be found in biotech. Indeed, I will end with some examples where greater attention to the role of academic centers would add to our understanding of biotech. However, the phenomena I will discuss here are more visible in microelectronics than in biotechnology because of several relatively durable features of the industry. The first is that semiconductor research depends on equipment and clean rooms that have become astronomically expensive since the early 1970s. These tools represent huge sunk costs that few single firms or universities can bear alone.

Second, most semiconductor product and process innovations are covered by patents that are held by multiple firms which cross-license their intellectual property. Thus, while firms compete vigorously to be the *first* to achieve a particular product or process innovation, they are rarely able to retain their monopoly for long. Even if a firm could keep exclusive control of an innovation, it wouldn't matter for long since, thanks to Moore's Law, semiconductor products are often obsolete by the time they reach the market. Semiconductor firms therefore use their in-house R&D to focus on pressing short-term needs – to gain first-mover advantage or to limit the window in which a competitor has sole mastery of an innovation.

Thus, since the late 1960s the most successful semiconductor firms have relied on external sources for longer range research (Bassett 2002). Firms with large in-house basic research capacities, such as RCA, AT&T, and IBM, have either gone bankrupt or shed much of that capacity. But because semiconductor innovations often come from unexpected directions, feed into a few product cycles, and then disappear, semiconductor firms need sources of long-range R&D that gather together a varied and changing portfolio of discoveries. Lacking their own, in-house long-range research capacity, semiconductor manufacturers instead rely on organizations which pool funding from multiple firms to hedge their individual risks, and which generate a varied portfolio of discoveries on which multiple sponsors can draw.

Such considerations might have been enough to stimulate the formation of industrial semiconductor research consortia and industry-oriented academic MRCs no matter what. Indeed, a few such centers formed in the 1960s and small, rudimentary consortia were founded in the early 1970s. However, in the U.S. the environment dramatically shifted in favor of institutional innovation in semiconductor research in 1975, thanks to the Japanese Government's announcement of a major initiative to bring that country's firms up to the state of the art in manufacturing very large-scale integrated (VLSI) circuits. American firms had already been losing market share to the Japanese semiconductor industry since the early 1970s. With the announcement of the VLSI program, panicked, nationalist calls to 'save' the American semiconductor industry erupted (Langlois and Steinmuller 1999). All of the institutional innovations I examine in this article came after 1975, and most explicitly referenced competition with Japan as a justification for innovation.

The first wave of centers and consortia

One response to the declining competitiveness and basic research capacity of U.S. semiconductor firms was the industrial research consortium, where member firms would contribute rotating personnel plus money for equipment and permanent personnel working on a coordinated menu of 'pre-competitive' research. In 1978 U.S. semiconductor firms spent 11% of their R&D budget in the form of technological collaborations or industrial consortia. By 1990, that figure had almost tripled (Zorpette 1990). Industrial research consortia seemed a logical institutional innovation to some leading industry executives and allies in government in the late 1970s because they believed that other countries – especially Japan – were far ahead of the U.S. in experimenting with these institutions. As one U.S. consortium, SEMATECH, put it in 1991,

> The formation of consortia to address semiconductors and supporting fabrication and material technologies started in 1971 in Japan. Before that, the French and other governments had been active in reorganizing their electronics companies into various industrial groups… Between 1971 and 1980 in Japan alone, five consortia were formed that had semiconductor development activities (including the VLSI Cooperative Society in 1976). In the late 1970s, Korea, the Republic of China, and the United Kingdom experimented with various kinds of joint efforts. (Sematech 1991)

Yet despite these international models, cooperative industrial research organizations faced an uphill battle in the U.S. because of antitrust laws. The Justice Department's interpretation of antitrust law also made consortia seem unnecessary prior to the late 1970s. That is, quasi-monopolistic firms such as IBM and AT&T were expected (or required by consent decree) to conduct and publicly disseminate basic research in order to avoid being broken up (Choi 2007). Smaller firms could therefore benefit from basic research performed by the giants without having to contribute anything themselves.

In the 1980s, however, conditions became more favorable to formal research consortia and less favorable to the quasi-monopolies' quasi-consortia. Tax breaks for money spent on basic research were cut back, encouraging large firms to reassign basic researchers to shorter term, proprietary tasks (Asner 2006). The Justice Department abandoned its threats to sue if large firms did not make enough of their in-house research publicly available. The Justice Department also broke up AT&T; in the ensuing settlement, a significant part of AT&T's research quasi-consortium (Bell Labs) was split off to form a formal research consortium (Bellcore) to conduct R&D for the newly independent Baby Bells.

Thus, the basic research capacity of the informal quasi-consortia on which Silicon Valley firms had been free riders declined through the 1980s. At the same time, the federal government lifted barriers to formal consortia, and in some cases even became an enthusiastic supporter of this relatively new organizational form. Thus, semiconductor firms turned to consortia as a way to make up for their shortfall in basic research. The most visible consortia were the Semiconductor Research Corporation (SRC) and the Microelectronics and Computer Technology Corporation (or MCC), both formed in 1982, and Sematech (or Semiconductor Manufacturing Technology), founded in 1987. Over the years many smaller and/or more time- and topic-delimited consortia formed alongside the larger, more generalist ones. All of these research consortia were aided by the industry's consortiumization of other activities. For instance, SEMI, a trade group for semiconductor process equipment manufacturers and materials suppliers, formed in 1970, and the Semiconductor Industry Association was founded in 1977 – the latter, as Saxenian (1992) puts it, to 'shape legislation', including the changes in antitrust law needed to legitimize consortia.

Institutional experiments such as research consortia rarely work on the first try. Indeed, proponents of consortiumization were aware that their first attempts might fail, but would be worth it if they led to further experimentation and eventually to answers to the challenge from Japanese manufacturers. As the White House Science Council Panel on Semiconductors put it in 1987,

> The current world competitive situation *demands* increasing cooperation both horizontally and vertically in the industry *as evidenced by the spontaneous emergence of the Sematech proposal*. Sematech is not necessarily the ideal instrument, but it is a significant step, a start. Indeed, it is generally agreed even by those advocating Sematech that it will not solve all the industries' problems. However, it will increase communication between elements of the industry, and may encourage new coalitions outside of Sematech, and may even facilitate industry restructuring. (White House Science Council 1987)

Thus, a few early consortia, most notably the MCC, faltered and eventually dissolved. In hindsight, critics blamed MCC's demise on difficulties in balancing the competing agendas of the member companies (Gibson and Rogers 1994). And yet, MCC's difficulties did nothing to diminish enthusiasm for consortia. If anything, MCC has come to be seen as a source of lessons which, having been learned, made consortia a permanent feature of the semiconductor industry (Browning and Shetler 2000; Corey 1997; Burger 1996).

Even before the emergence of the major semiconductor industry consortia, academic centers with strong ties to that industry started to form. Indeed, there had been a few academic centers focused on microelectronics in the late 1950s and early 1960s, but these were generally ad hoc mechanisms for a few professors to pool equipment. Often, these faculty members had experience in industry (Kenney, Mowery, and Patton 2014), but research and pedagogy – rather than industrial partnerships – were these organizations' core purpose at the beginning. In the late 1970s, though, academic microelectronics centers started to form with the explicit aim of aiding industry.

Contemporaries observed that this trend paralleled the emergence of professorial startups in the biotech industry. However, competition with Japan in semiconductors generally loomed larger than biotech as a stimulant to academic microelectronics researchers' turn toward industry. As *Science* put it (Norman 1982),

> While attention has been focused on the expanding links between academic biologists and the corporate world, a second revolution in university-industry relationships has been taking place in a different field. Electronics companies, faced with growing competition from Japan and fearing a shortage of well-trained Ph.D.s, are pouring unprecedented amounts of cash into university electrical engineering and computer science departments.

Thus, the same conditions that led to the formation of industrial consortia were visible in the late 1970s to academic entrepreneurs who concluded that those conditions provided an opportunity to forge closer ties with semiconductor firms. Some of those ties were bilateral, but many were 'consortium-ized' – i.e. both risks and benefits were shared across many contributing firms – through the mechanism of an academic center.

A prominent early example which illustrates the incentives and initial obstacles to such centers was Carver Mead's Silicon Structures Project at Caltech. This center received considerable press attention at the time; more recently, Elizabeth Popp Berman (2012) has examined it as an early instance of a 'university-industry research center'. My analysis of the Caltech center (and several others I'll discuss) is indebted to Berman's, but what I contribute is a perspective on such centers from the viewpoint of an industry (semiconductors) that was simultaneously exploring other options (particularly consortia) to obtain the same benefit that Mead's and other academic centers purportedly offered. Thinking about university centers in terms of their interactions and competition with consortia offers insight into why centers such as Mead's formed (and closed) when they did, why they were configured in particular ways, and why they were able to secure certain kinds of patronage.

Mead was a long-time friend and collaborator of Intel's cofounders, Robert Noyce and Gordon Moore – for several years even flying to the Bay Area from Pasadena for weekly meetings with Moore (Brock 2006). Mead was equally famous for collaborations with other industrial researchers, most notably Lynn Conway of Xerox. Yet despite his close ties to U.S. firms, he still found it hard to gain their attention. For instance, when he made optimistic predictions for the miniaturizability of electronic components in the early 1970s, 'the people who were listening the closest were the Japanese', rather than his friends in the U.S. semiconductor industry (Mead 1980).

One of the consequences of miniaturization was that integrated circuits became more complex, and therefore the design of chips became more labor-intensive. In the mid-1970s, Mead switched from studying miniaturization per se to developing automated means of designing chips. As Mead put it,

> back in 1970 … there were only a few tens of people-months involved in designing a chip, and everyone said 'well, why don't you university folks go and mind your business and play with your toys because we don't think we have the problem. (Mead 1980)

Thus, he could see that he needed some institutional innovation to get firms to recognize that a university could supply the long-range research that was disappearing from industry: 'one of the functions of a university is to do a fair bit longer look ahead than it's possible to do in a rapidly emerging and very competitive industry' (Mead 1980).

Mead called his institutional innovation a 'project' rather than a 'center' – perhaps an indication of how fluid the terminology still was. Yet it was, in fact, a center – it 'centralized' the research outputs of a small coalition of faculty members and their students. It also centralized inputs, by pulling together funding from 'IBM, Xerox, Burroughs, Hewlett-Packard, Digital Equipment Corporation, Intel, and Honeywell' (Mead 1980). Many of the same firms would soon also invest in industrial research consortia such as MCC – precisely in order to gain the same 'fair bit longer look ahead' that Caltech offered. In its operations, too, the Silicon Structures Project borrowed many of the traits of an industrial consortium. It had in-house 'staff' (students) who worked with rotating researchers from the 'consortium members' (industrial sponsors):

> Each of these [firms] sends a scientist on a rotating basis to work with us …. They come and work with our students …. [thereby] transferring the lore that comes in an academic research environment back into the companies …. It allows the university to do what it's the best at, looking very far ahead, taking risks, looking at things whose outcome is very uncertain. It also uses the industrial organizations for the things they're the best at. And in fact we get a fair bit of help with project management kinds of things and things we'd otherwise have to start stepping outside of our role as a sort of a blue sky research organization. (Mead 1980)

That is, Mead's center was financed like a consortium, configured technology transfer in much the same way as a consortium, and even brought in corporate project management methods to help it operate less like an academic unit and more like a corporate research lab, albeit one not housed in any particular firm – just like an R&D consortium.

Enter the state(s)

Mead's center was somewhat unusual in having relatively little support from government. In most cases, though, academic entrepreneurs were spurred to form (or to expand) industry-oriented microelectronic research centers by inducements offered by federal and state agencies. Institutional entrepreneurs within government fostered the emergence of both academic MRCs and industrial semiconductor research consortia, and built thick, varied connections among them. The federal government was a member of some consortia, most notably Sematech (until 1996), while many academic centers that conducted industry-sponsored research needed extra funding from the state to support operations and purchase equipment. Government agencies also prompted formation of a few consortia with industrial, academic, and government participation – such as the Consortium for Superconducting Electronics in 1989, which united AT&T, IBM, MIT, and Lincoln Lab (a DoD laboratory operated by MIT).

One prominent example of federal intervention was a 1976 NSF-sponsored competition for a National Research and Resource Facility for Submicron Structures (Mody and Choi 2013). The NSF received about 15 proposals for the NRRFSS, several of them from small coalitions of universities and government laboratories, including: a University of Pennsylvania/Drexel University/Lehigh University team; a University of Colorado/National Bureau of Standards (Boulder) collaboration; and the second-place finisher, a joint proposal from MIT proper and MIT Lincoln Lab. In the end, Cornell won, but the competition inspired the formation of a number of similar centers and facilities in the late 1970s and early 1980s. The academic institutional entrepreneurs who had answered the NSF's call by piecing together assemblages of personnel, equipment, and money were well-positioned to continue their institutional entrepreneurship even when they lost the NRRFSS competition. For instance, the leader of the MIT Lincoln Lab proposal, Hank Smith, was invited to move from Lincoln Lab to MIT to found a Submicrometer Structures Laboratory which has competed with the Cornell facility for almost 40 years.

As the unwieldy name implies, the NRRFSS was designed both to rent out expensive semiconductor manufacturing equipment ('resource') and conduct experiments on the submicron scale ('research'). The NSF eventually imposed a third mandate, that of providing advice on how to establish and run such a facility. Academic researchers were intended to be the primary beneficiaries of all three missions, but the NRRFSS was also expected to serve industrial users. It was also intended to indirectly aid industry by making it easier for academic users to conduct industry-oriented research without unduly burdening firms. As Jay Harris, the NSF officer who put together the NRRFSS competition, recalled, when he was a professor at the University of Washington.

> In the late '60s and early '70s, I used to visit various industrial laboratories to try to get some help in making small optical structures. I got my best reception at the Hughes research labs in Malibu, from a guy named Ed Wolf, who was working with electron beams, but Ed didn't really have time to devote to supporting academics trying to work over their heads. (Harris 2003)

When Harris moved temporarily to the NSF, therefore, he began lobbying his superiors for a national user facility that would rent expensive equipment to academic researchers.

Initially, Harris' proposal faced a significant skepticism from industry (including Robert Noyce of Intel), the National Science Board, and the military. By organizing workshops and gathering testimonials from stakeholders, however, Harris legitimized the NRRFSS as a new way for government to bring academic researchers in closer contact with the industrial state of the art. In effect, Harris acted as an academic entrepreneur working temporarily on behalf of the state. Notably, one of the most common justifications offered for the NRRFSS was that it would help the U.S. semiconductor industry. As a report from one Harris' workshops put it,

> adding to the urgency of the need for research in the submicron domain is the effort made by our international competitors to leap-frog the US technology in this field. The most noteworthy program is the Japanese decision to spend $233 million in the next four years to develop submicron device research and fabrication capabilities with their industry-university teams. (Chang et al. 1976)

That is, institutional entrepreneurs were mobilizing Japan's VLSI circuits program to legitimize academic microelectronics centers even before they were using it to legitimize industrial research consortia.

After the NRRFSS was founded, Harris' former industrial colleague Ed Wolf became its director. There, Wolf cultivated a variety of university–industry interactions. Corporate researchers, especially from East Coast powerhouses like IBM, General Electric, and AT&T, developed collaborations with Cornell faculty affiliated with the facility; corporate users occasionally rented time on NRRFSS equipment; and companies looking to build their own clean rooms or buy new semiconductor process equipment looked to Cornell for advice. A report from 1986 summarized such interactions, including examples of all three involving one company, General Electric:

> GE had an engineer in residence at NRRFSS for a year to learn MBE [molecular beam epitaxy], electron beam lithography and device processing for high speed GaAs [gallium arsenide] devices. He then returned to GE and established a similar processing capability …. Strong interaction continues between GE and Cornell. NRRFSS is continually called on to help/advise other companies and universities in setting up similar laboratories, such as Varian, GE, McDonnell Douglas, the Jet Propulsion Lab, Hughes, Caltech, University of Michigan and University of California San Diego. Over the last several years we have advised more than forty organizations. (Ballantyne 1986)

The NRRFSS also established an industrial affiliates program that strongly resembled a consortium in miniature: by 1986, 37 firms were each paying Cornell $8500 per year for previews of faculty research and opportunities to recruit promising graduates (Cornell University News Bureau 1981).

Like other academic centers, the NRRFSS didn't just borrow features of industrial consortia – it also partnered directly with such consortia (in addition to its bilateral relationships with individual firms). The most important such partnership was with an SRC Center of Excellence in Microscience and Technology located on the Cornell campus. SRC established Centers of Excellence at many schools, including several affiliated with the academic centers that I'll discuss below. Several directors of academic MRCs or facilities (including Ed Wolf) joined the SRC's University Advisory Committee and thereby influenced the consortium's research agenda – a notable way in which centers and consortia were commingled organizational forms.

One reason for the commingling of centers and consortia is that the latter often require an on-campus broker to mediate their interactions with universities. A center is, in many ways, the optimal form for such a broker. Interfacing with an entire university or even a department is inefficient for a consortium, since these organizational forms rarely make quick or uncontested decisions. Interfacing with a single faculty member guarantees faster response, but not breadth of knowledge – and when the consortium's needs change, the individual professor's expertise may no longer be relevant. An academic center, however, can act relatively quickly and coherently, and yet can still bring the expertise of a broad and flexible array of faculty to bear on the consortium's ever-evolving needs.

A local supply of well-funded academic centers (staffed by world-class faculty) was therefore a high priority for the semiconductor consortia that formed in the 1980s. Hence, state governments energetically fostered academic centers in order to attract consortia headquarters to their regions. The Microelectronics Center of North Carolina (MCNC), for instance, formed in 1981 with support from the state and a coalition of five universities; the MCNC was integral to North Carolina's success in attracting the SRC's headquarters (Casey 1981; Whittington 1985). Similarly, when the state of Texas wanted to woo the MCC to Austin in 1983–1984, part of Governor Mark White's pitch was that the state would fund a new MRC at the University of Texas (University of Texas Office of Public Affairs, 1984).

The Texas state government's successful bid to build Austin into a high-tech region was facilitated by – and immensely valuable to – academic institutional entrepreneurs within both the University of Texas and Texas A&M University. As Jack Kilby (co-inventor of the integrated circuit and an adjunct faculty member at the latter university) reported to his former colleagues at Texas Instruments in 1983,

> I have inadvertently become involved in attempting to convince MCC that they should locate in Texas. Austin is one of the four sites left in the race. One of the primary MCC concerns is the quality of the university facilities which may be available. Since UT has very little work in the microelectronics area, A&M has been asked to help. (Kilby 1983)

Kilby was probably hoping that MCC's presence would benefit the pioneering pedagogical 'fab' (integrated circuit fabrication line) at Texas A&M University which he and colleagues were trying to place at the center of the undergraduate electrical engineering curriculum.

Kilby was slightly off-target in his assessment of the University of Texas, however. In 1982, a prominent semiconductor researcher from the University of Illinois, Ben Streetman, had moved back to the University of Texas (where he had done his PhD) and had started to informally pool research equipment with other faculty members. It was Streetman who took advantage of the MCC site selection to convert those informal efforts – with state support – into the MRC. Then in 1986–1987, when the state was lobbying a second consortium, Sematech, to put its headquarters in Austin, Streetman leveraged the opportunity to convince the governor to fund a brand new, state-of-the-art facility for the MRC (University of Texas Office of Public Affairs 1987).

Texas wasn't the only state to try using an academic center to lure Sematech. As Leslie (2001) has shown, New York's Albany region offered the consortium a Center for Integrated Electronics at Rensselaer Polytechnic Institute but, 'in the prevailing political climate [of the late 1980s], Texas simply had more clout than New York'. Apparently the prevailing climate has changed, however, since Sematech's headquarters were recently poached away from Austin to the Albany region in large part by the promise that the State University of New York system would build a Computer Chip Commercialization Center, a Chemical Mechanical Planarization Center, and other centers to serve as the consortium's local academic partners (PRWEB 2014).

Stanford un-exceptionalism

There are many different ways for firms to organize the consortiumization of their activities both inside and outside (and at the thick boundary of) the academy. Each of the consortia I've described was structured differently, and there was even greater variation in the organization of the academic centers I've mentioned. Over time, however, many of these centers' practices converged, through a variety of mechanisms: some (e.g. Cornell's NRRFSS) specialized in propagating their model; there is evidence that centers kept tabs on their peers and copied successful strategies; and of course personnel (faculty members and former students) moved from one center to another, transplanting norms in the classic model of institutional isomorphism. In addition, in the late 1970s the Institute of Electrical and Electronics Engineers (IEEE) began organizing biennial 'University/Government/Industry Microelectronics' conferences, at which leaders of academic microelectronics centers would report on their practices. Notably, by the early 1990s (if not earlier) that conference series was sponsored by Sematech and SRC.

Despite such convergence, however, there was and is variation among academic centers aligned with the microelectronics industry, in part because that industry took different forms in the regions served by different universities. Moreover, while this article is primarily about the resemblances and linkages between industrial *research* consortia and academic *research* centers, it's important to remember that industrial consortia and universities do many things other than research. For instance, some academic microelectronics centers positioned themselves as aids to regional economic growth not by partnering with national consortia, but with local high-tech incubators. Obviously, an incubator is different from Sematech or SRC; still, incubators consortiumize many of the things most relevant to high-tech entrepreneurs – real estate, pools of investors, administrative costs, personnel, expertise, etc. And like larger R&D consortia, incubators sometimes found it useful to interface with universities through dedicated centers.

For instance, in the 1990s the founders of the Center for Nanotechnology at the University of Washington convinced upper administrators to give them control of an existing microfabrication user facility located in a university-affiliated tech incubator, the Washington Technology Center (Spelman 1997). The WTC Microfabrication Laboratory was originally founded in anticipation of semiconductor manufacturing firms such as Intel and Taiwan Semiconductor opening sites in Washington State (Yager and Darling 1998). The founders of the Center for Nanotechnology argued, however, that firms would have easier access to the university through a facility located in the incubator but controlled by an academic center:

> other Centers have experienced that well maintained user facilities act as focal points to build long-lasting relations between industry and research institutions. They create an environment in which scientists from industry can meet and collaborate with students, post-doctoral fellows, and faculty while pursuing mutual research interests. (Vogel 1996)

Indeed, sometimes centers act as more than just 'focal points'. Because clean rooms and semiconductor process equipment are so expensive, renting time on academic equipment is sometimes much more cost-effective for cash-poor start-ups than buying tools and building a fab. In at least one instance (at the University of Texas), a local start-up actually had semi-permanent office space within the academic user facility. That may have been a slightly unusual arrangement, but other user facilities I've visited have been very happy to have local start-ups use their equipment on a near-daily basis – i.e. to help start-ups cut costs by sharing the costs and benefits of their tool base with other users through an academic quasi-consortium.

Other academic microelectronics centers drew on firms' consortiumized *political* activities. For instance, in 1983 Ray Warner, one of the founders of the University of Minnesota's Microelectronics and Information Science (MEIS) Center, appealed to 'the Minnesota High-Tech Council (MHTC), a fairly active committee of local captains of industry, and the Governor' to force the president of the university to 'stabilize and then rebuild' the university's microelectronics research capacity (Warner 1983). Similarly, when the NSF tried to pull funding from the Cornell NRRFSS in 1985, the facility mobilized the New York Congressional delegation, its industrial affiliates and users, and the corporate executives on its advisory board to lobby the NSF to reverse its decision.

Almost all these variations on the center–consortium relationship are contained in the most hybridized example of an academic center and/as an industrial consortium: the Center for Integrated Systems (CIS) at Stanford University. There is, of course, already an abundant literature on Stanford's relationship with Silicon Valley – probably too abundant, since as Steve Shapin (2008, 160) notes, discussions of academic entrepreneurship often mistake elite universities such as Stanford for the norm. I don't dispute the point, but in terms of how Stanford has managed its MRCs *as*, and in collaboration with, industrial consortia, it is exceptional only in the *degree* to which it combines and amplifies traits which are also evident at less elite schools. Moreover, federal policymakers – particularly in the National Science Foundation – seem to have viewed Stanford and Cornell as models to be copied by academic MRCs elsewhere. I've discussed Cornell already. Let me now examine Stanford with a view to what it can tell us about centers and consortia more generally, before finally bringing Stanford and Cornell into the same frame.

As Lécuyer's (2005) classic 'What Do Universities Really Owe Industry?' shows, the CIS represented the culmination of more than 30 years of Stanford's steadily thickening ties to the local semiconductor industry. The CIS was the brainchild of John Linvill, the longtime chair of the university's Electrical Engineering department, and his frequent collaborator, James Meindl, founder of Stanford's Integrated Circuits Laboratory (ICL). Both men were serial technological inventors, institutional innovators, and commercial entrepreneurs, having cofounded a company, Telesensory Systems, in 1970.

Curiously, Meindl's ICL would almost certainly have beaten Cornell in the NSF's 1976 submicron facility competition had he chosen to compete. Yet Meindl was notably helpful to the new centers that arose in the wake of the NSF competition, even serving on the NRRFSS advisory board. As an MIT faculty member reported to his employer's Submicrometer Structures Laboratory after a visit to Stanford in 1977,

> While it may seem strange to us, Jim Meindl said that he thought MIT's entry into the IC field would legitimize it, and give more emphasis to Stanford's program. I cannot overemphasize that everyone I met was *most* cordial and friendly, and eager to cooperate. (Wolff 1977)

However, Meindl and Linvill could also see that the emergence of new academic microelectronics centers meant Stanford's claim to unique competence was eroding, and that they therefore needed to transform the ICL into a wholly new kind of organization. Thus, in about 1978 they put together plans for a center that would unite the ICL with three other microelectronics and computing centers to form a single organization that would 'integrate' research from solid-state physics through computer architecture design. They began lobbying the NSF, and later the Defense Advanced Research Projects Agency (DARPA), for research support, and at the same time approached leading industrial research managers, such as Lester Hogan of Fairchild Semiconductor, to join an exclusive (and expensive) affiliates program. By 1982, they had persuaded 18 firms to make a $750,000 up-front payment plus $100,000 in annual dues (Anonymous 1982). That rate equaled the annual dues paid by sponsors of Caltech's Silicon Structures Project (Berman 2012, 127). CIS dues eventually went up, but the number of affiliates remained around 18–20 for the next 30 years.

What did affiliates get in return? The *CIS Newsletter* let Hogan explain:

> Dr. Hogan points out that Japan, whom he feels is America's main competition in high technology, has employed somewhat the same approach to basic research on problems crucial to Japan's economic future …. 'To win against foreign competition,' says Dr. Hogan, 'we need programs like CIS, sponsored by industry, at a half dozen more of our best universities, coupled with renewed vigor for basic research by industry itself'. (Vollmer 1982)

In other words, industry needed the CIS for the same reasons that it needed consortia: to overcome competition from Japan and to rebuild basic research capacity. And, with dues more than an order of magnitude higher than ordinary affiliates programs (such as that at Cornell's NRRFSS), the CIS was more consortium-like than most centers in the degree of influence sponsoring firms had over research. As at Caltech's Silicon Structures Project, the CIS' initial setup allowed member firms to send researchers on sabbatical at Stanford, partly to provide a conduit for technology transfer to (and from) the firm.

The CIS differed from the Silicon Structures Project, however, in its longevity, running almost thirty years longer than the Caltech center. Berman (2012, 128) explains the Silicon Structures Project's demise as a result of difficulty matching academic and industrial expectations for students. She also notes that the center's small size (industrial rotators far outnumbered affiliated faculty) made it unsustainable. The CIS, on the other hand, nearly matched the size of some consortia: by 1985 its affiliated faculty were using the CIS for 173 different projects. As at some other academic centers, some of those projects were supported by industrial consortia, such as an SRC Center of Excellence in semiconductor manufacturing systems. Yet Stanford's size and proximity to Silicon Valley meant it could sometimes reverse the usual arrow of influence between centers and consortia: for instance, in 1987 the CIS bragged of 'participating in the planning of SEMATECH' (Losleben 1987).

Of course, as a university, Stanford was supposed to train students who would then be recruited by sponsor firms – not the usual arrangement at a more purely industrial R&D consortium. Even there, though, the CIS was more of a hybrid organization than might appear at first glance. As the *San Jose Mercury* noted in 1981,

> Intel Corp. of Santa Clara, for one, has not rallied to Stanford's request for money [for the CIS], even though Intel Vice Chairman Robert Noyce is one of the Stanford fundraisers. 'We were concerned about the fact we were getting relatively few graduates from Stanford… Many Stanford graduate students are on leave from other companies or are foreign students … but that's another story,' said Noyce, his voice fading. (Richards 1981; ellipsis in original)

Noyce also seems to have worried that Intel would end up funding research that others would commercialize – a problem that confronted non-academic consortia as well, and which eventually doomed the MCC. As a local paper quoted him, 'The benefit is spread much more broadly than the cost. The non-participants in CIS will benefit just as much as the participants. Unless a participating company looks at the broader benefits, the winning strategy is not to participate' (Duenwald 1982).

Academic freedom (of choice)

As the quote from Noyce indicates, not everyone in the semiconductor industry was convinced that long-range research should be consortiumized through academic centers, or even at all. Noyce expressed his own preference by taking over as Sematech's first CEO and then steering the consortium away from basic manufacturing research and toward improving relations between semiconductor manufacturers and equipment vendors (Berlin 2005, 297, 298). Some early academic centers, such as Mead's Silicon Structures Project, stagnated or disappeared when they failed to live up to the promise of aiding industry. Yet today the academic MRC is a thriving organizational form, with many dozens of examples across the U.S. and the world. How, then, did the entrepreneurs of this particular institution secure its legitimacy?

In part, they did so by being responsive to their sponsors' demands. For instance, in 1982 the National Science Board judged that Cornell's NRRFSS was inadequately aiding external users and therefore threatened to cut off its NSF grant. As a result, the facility appointed a new associate director for the User Program, and four years later the proportion of external users had risen to 60%, including 12% of users from industry (National Research and Resource Facility for Submicron Structures 1985). By that point, as well, a third of research projects conducted in the facility were funded by industry (Ballantyne 1986). Similarly, Stanford's CIS suffered from early complaints that sponsor firms weren't able to get specific research objectives on faculty members' agendas. Thus, the center developed a new mode of cooperation: FMA teams (Faculty member–corporate Mentor–graduate Advisee). Through these teams, graduate students' projects were essentially *co-directed* by a faculty advisor and an industrial researcher (Linvill 1990). The CIS was also quick to develop online systems for disseminating research to partner organizations, probably at the urging of federal and industrial sponsors (Losleben 1987).

By the late 1980s, however, the economic and political environment in which the NRRFSS and CIS and their peers were founded was beginning to change in ways that made it necessary for them to find new sources of support. The semiconductor industry was becoming less vertically integrated, with much manufacturing outsourced to 'foundries'; nationalist rhetoric gradually died down, though it was not until 1998 that an Asian firm finally became a CIS sponsor; and the technological paradigm of semiconductor manufacturing settled (perhaps temporarily) on optical lithography, leaving academic experts in other techniques adrift. Academic centers therefore had to work harder to interest industrial patrons. As Jim Plummer, Meindl's successor as director of the Integrated Circuits Lab portion of the CIS, put it in 1988,

> The only available source of funds at present to support [the ICL] is the CIS sponsors annual contribution. We are actively seeking external funding, but it is not an easy matter to 'package' this activity in a way that is attractive to government sponsors. Everyone (CIS Sponsors included) wants to support leading edge research. To the extent that chip building is regarded as not leading edge or in direct competition with industry, it is not interesting to sponsors. (Plummer 1988)

To survive, the CIS, NRRFSS, and their peers took full advantage of the flexibility of academic institutions – a flexibility largely denied to conventional industrial R&D consortia. This point somewhat cuts against the grain of much recent work by historians, sociologists, and STS scholars on the commercialization of academic research. Some scholars in this tradition (Shapin 2008) argue that the variety and commingling of industrial and academic organizations mean that it makes no sense to draw blanket distinctions between these domains, especially not distinctions predicated on a mythical norm of academic freedom. Others (Rabinow 1996) argue that in fact corporate research is more free than its academic counterpart. More anxious scholarship (Mirowski 2010) sees universities since 1980 as giving up on academic freedom in a rush to adopt corporate models. I don't disagree with these claims; indeed, they accord well with my argument that industrial semiconductor research consortia and academic MRCs were commingled and co-emergent forms which blurred any facile distinction between corporate and academic research. That said, academic centers' embeddedness in a university ecology did make a difference by providing a flexible menu of options in the face of changing technological, business, and political conditions.

For one thing, the CIS and its academic peers were able to participate in *university* consortia just as easily as they could partner with industrial ones. As Hoddeson, Kolb, and Westfall (2008) argue, in fields such as high-energy physics the expense of research equipment makes it impossible to build state-of-the-art experiments without forming large coalitions of universities and state/provincial or national governments. The tools and clean rooms needed for microelectronics research are not in the same league as particle accelerators, but commercial chip manufacturing has almost reached the point where only coalitions of firms can afford a state-of-the-art fab. By extension, no single university can presently afford a full suite of the equipment needed for state-of-the-art microelectronics research. A few state university systems have approached that problem by consortiumizing research activities among multiple schools – I've already mentioned the MCNC and New York State's Computer Chip Commercialization Center, both of which were attached to coalitions of universities rather than a single school.

At the national level, since 1994 NSF funding for academic microfabrication user facilities has been funneled through continent-spanning consortia of universities which, *in toto*, provide users with a full complement of tools: first through the 5-member National Nanofabrication Users Network and then the 13-member National Nanotechnology Infrastructure Network. Both the NNUN and NNIN were led by the descendant of Cornell's NRRFSS and 'co-led' by Stanford's CIS. The NNIN has recently been replaced by a National Nanotechnology Coordinated Infrastructure which operates in a similar manner.

Faculty who are affiliated with academic centers also have the freedom to form partnerships with a broad range of industries. It's hard to imagine Sematech or the SRC as focused on anything other than the needs of the semiconductor industry. Academic microelectronics centers, however, can draw on faculty from almost any university department, and therefore can facilitate those faculty in bringing microelectronics and semiconductor expertise and equipment to bear on a wide range of industrial applications. For instance, one NNIN member facility that I visited in 2009 (Georgia Tech's) proudly told me about their partnership with one of the leading firms in the *paper* industry! Much more common have been linkages between academic microelectronics centers and the health and biotech industries. Of the thirteen schools in the NNIN, five listed a life science area as a core field of expertise, and three were predominantly oriented to biomedicine.

That connection to biomedicine was partly mandated by the NSF, and partly a natural consequence of skyrocketing federal support for the National Institutes of Health in the 1990s. But it was also partly a reaction to notable examples of faculty entrepreneurship in biotechnology arising from the leading academic microelectronics centers. One such was the 'gene gun' – a technique for moving foreign DNA into the nuclei of plant cells

– co-invented by the director of the NRRFSS, Ed Wolf, and a Cornell horticulture professor, Sanford (2000). Nelson (2012) describes the gene gun as resulting in 'the largest royalty payment to the Cornell Research Foundation up to that date and … one of the most 'readily recognized financial successes' in the history of Cornell technology transfer', thanks to a start-up company founded by Wolf and Sanford, which licensed their Cornell patents and turned the technique into one of the most widely used tools for creating early genetically modified crops. Another project much touted in the NRRFSS' promotional materials was a study of fungal growth on microfabricated pores – work of great relevance to the *wine* industry in New York state's Finger Lakes region.

Similarly, the Stanford CIS' proximity to the San Francisco biotech cluster led to development of DNA microarray or 'gene chip' (trademarked as GeneChip©) technology. As Lenoir and Giannella (2006) have shown, the DNA microarray arose through a *mutual* spillover of industrial research into academia and *vice versa*. The leading company, Affymetrix, was a spin-off of a second-generation biotech firm, Affymax, looking to develop high-throughput methods for varying and screening molecules for drug discovery. As Doogab Yi (2010) describes it, an Affymax

> photochemist, [Michael] Pirrung, suggested that light-controlled synthesis of polymers might be a productive and inexpensive way to create diverse sets of random chemical molecules …. Pirrung drew an analogy with the production of silicon chips using photolithography …. Following an innovative technology used in the semiconductor industry, VLSI (very large-scale integration), they decided to develop VLSIPS. (very large-scale immobilized polymer synthesis)

Since Affymax had deep Stanford roots, Pirrung soon made contact with the CIS and one of its resident experts in VLSI, Fabian Pease, to help them move from VLSI to VLSIPS. The result, according to Lenoir and Giannella, was that 'Pease has been co-inventor … on several key Affymetrix patents, and he has continued to maintain a consulting relationship with Affymetrix'.

Academic centers, then, can make far-flung alliances and pursue promising research trajectories toward a wider range of possible outcomes than an industrial consortium can. It's quite possible that this dilution of influence actually benefits semiconductor firms, since enough of the research done at these centers still concerns microelectronics, but with that industry now able to share the burden of supporting the centers. Yet the dilution of semiconductor industry influence is also of benefit to the host university and society at large – especially since the possibilities that an academic center can follow are as likely to be epistemic as commercial. Basic, curiosity-driven research areas have benefited enormously from the equipment, expertise, and industrial funding associated with academic MRCs. MIT's Submicron Structures Laboratory, for instance, has become well known for the development of diffraction gratings used in the fairly esoteric field of *astrophysics*.

Conclusion

Despite this branching out, academic MRCs are still very interested in working with both individual semiconductor firms and industrial semiconductor research consortia. Some of the commingling of these two organizational forms that took place when they first emerged still occurs – for instance, state governments' use of academic centers to lure consortia headquarters. In other ways, though, their relationship has changed substantially. Some scholars, for instance, have argued that the main role for semiconductor consortia today is to cultivate a large stable of diverse academic teams – and to encourage those teams *not* to think too much about medium-term or direct relevance to the semiconductor industry (Khan, Hounshell, Fuchs, 2015, 30, 31). Others argue, however, that state agencies – particularly DARPA – have figured out how to nudge constellations of industrial and academic researchers toward productive outcomes in ways that transcend the need for industrial consortia (O'Reagan and Fleming forthcoming). Either way, it is clear that academic researchers need, and can find, a more varied portfolio of sponsors today than they could in the 1980s, and therefore that relationships between academic microelectronics centers and industrial semiconductor consortia are more attenuated than before.

In other words, both academic centers and industrial consortia are continuing to evolve and innovate as their environments evolve, with help from institutional entrepreneurs inside and outside of both types of organizations. Those dynamics of mutual observation and co-emergence have been present since at least the late 1970s, when entrepreneurs in industry, academia, and government all perceived the U.S. semiconductor industry as losing its ability to do basic research and as existentially threatened by competition from Japan. Institutional entrepreneurs in academia (e.g. Carver Mead or John Linvill) saw that as an opportunity to found a new kind of academic unit. Some institutional entrepreneurs in industry (e.g. Robert Noyce) believed that circumstances merited a new kind of industrial organization – the consortium – and were only grudgingly supportive of academic centers. Other industry executives (e.g. Les Hogan) were more inclined to see academic centers and industrial consortia as complementary. Institutional entrepreneurs in government, meanwhile, pursued a variety of strategies which offered resources and legitimization to entrepreneurs in industry and academia – without the help of state actors like Jay Harris, many academic centers and industrial consortia would not have gotten started.

Which is to say: the historian's task in understanding academic institutional entrepreneurship can only get more complicated. Interpreting how, why, and when academic actors introduce new institutions is difficult enough. But any conclusions we might offer are incomplete unless we also take into account actors in other organizations and even in other domains of social life who can aid or hinder the academic actor. The reward for our effort in drawing those connections, however, is that we make our studies relevant in understanding phenomena far from the university. The story of academic research centers in the U.S., for instance, sheds light on the travails of American manufacturing, on diplomatic relations between the United States and Japan, and on the interplay of state and federal governances – connections that remain invisible when the story is only told from the perspective of the academic actors.

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